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STIFFENING LOCK GATES BY PRESTRESSING DIAGONALS

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WATERWAYS DIVISION

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STIFFENING LOCK GATES BY PRESTRESSING DIAGONALS

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ABSTRACT

This paper presents a method for the control of the warping or twisting of mitering-type navigation lock gates which occurs when the gates are swung through the water. The gate leaf is analyzed torsionally and the function of the diagonal members in resisting torsional forces is explained. Expressions for torsional deflection and corresponding stresses in the diagonal members are developed. Diagonal members are prestressed to increase their effectiveness. The steps to take in applying the theory to design are given and the field technique to use in prestressing is presented.

INTRODUCTION

The warping or twisting of mitering-type navigation lock gates which occurs when the gates are swung through the water has often posed some serious problems. In one navigation system in the United States there are a number of locks in which the gates are all of very similar design and all of the gates twisted excessively when they were being opened or closed. To remedy this situation, new machinery was ordered so that the speed of operation was cut in half thus causing less of a twisting force. This correction involved considerable expense but no simple method of stiffening the gate leaves was known at that time.

Gates which were thick seemed to twist less than thin gates, and it had long been known that diagonal members on the gates prevented much of the twisting, but there was no rational method of designing or of determining in advance how much a given gate would twist in operation. Diagonal members were assumed to carry all or a part of the dead-load shear in the leaf and although this design assumption led to diagonals which looked reasonable, the method has no rational basis and the results of applying it were sometimes disastrous.

The skin plate on most lock gates is so rigid in its own plane that it carries practically all of the dead-load shear and the amount of the shear carried by the diagonals is negligible. The actual function of the diagonal members is to make the gates torsionally rigid and this article explains how that can be done. This design has been used successfully on several new lock designs in the United States and has even been applied to the stiffening of gates on some older locks. In the latter case the gate leaves were analyzed and the existing diagonals prestressed without altering the leaves structurally in any way.

The first new design using this method of torsional analysis involved gates for a lock which is eighty feet wide. Each leaf of the gate at the

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downstream end of the lock is fifty-six feet high and forty-five feet wide but is only three feet thick. Such a thin gate had never been tried before, but it operates under all conditions with no noticeable twist. Indeed it is so rigid that the lock operators even swing the leaves back and forth to clear floating masses of ice out of the channel in the winter time.

Analysis

Consider the surface illustrated in figure 1 as representing the surface of a lock-gate-leaf panel including the skin plate and the vertical end girders or diaphragms. In the plan view the surface may be of any shape whatsoever. The vertical lines gj and fk are drawn a small but finite distance apart on the surface. Now let the element fgjk of the surface be warped in such a way that the side gj rotates about the lower edge jk into the new position g'j. The other portions of the surface remain rigid so that the whole segment gjbc also rotates about the axis jk but it undergoes no twisting. If the angle (g'fg) in the plan view is denoted by α, the angle through which g'g rotates is

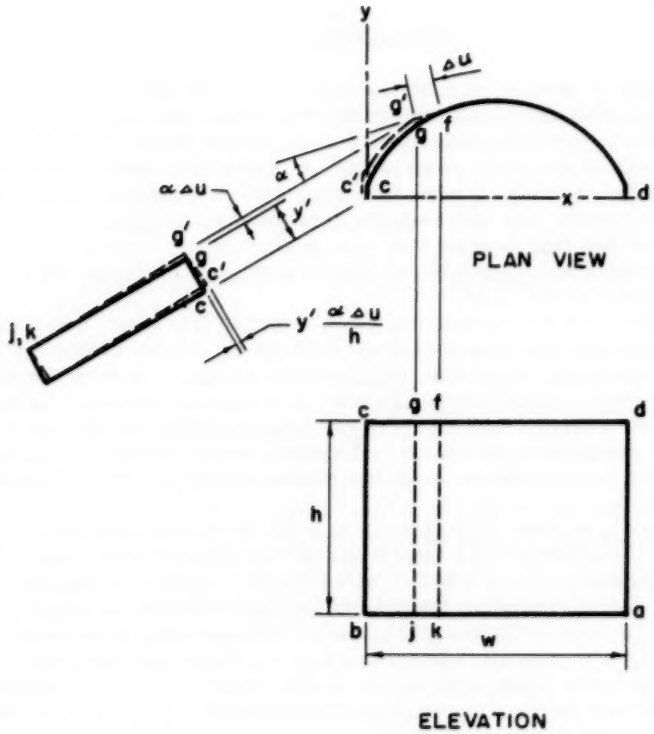
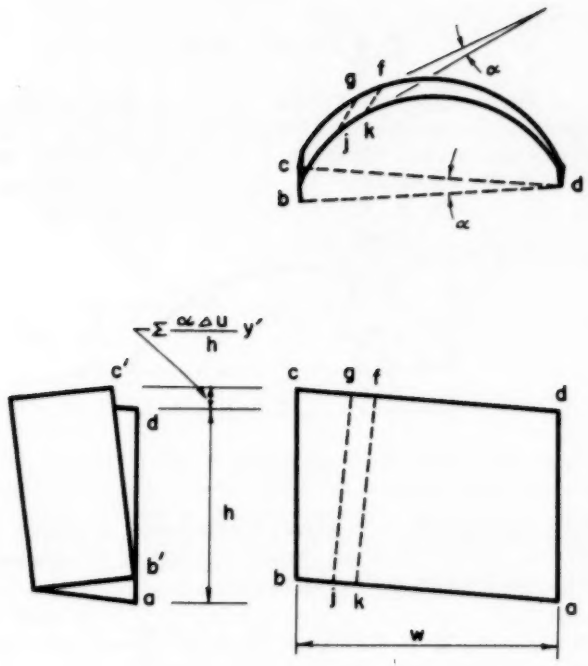


Figure 1



Orthographic projection of twisted surface

Figure 2

$(\alpha \Delta u)/h$ and the point c is displaced vertically by an amount $\frac{(\alpha \Delta u)}{h} y'$, it being understood that the angle α is small. If a lock-gate leaf is twisted, the horizontal girders prevent any change in the shape of any horizontal cross section as seen in the plan view, the warping of the sections producing only second order changes as seen in the plan view. Each element of the surface, therefore is warped by the same amount, α, (figure 2) and the total vertical displacement of point c is

$$\frac{\alpha}{h} \Sigma \Delta u \, y'$$

But $y' = y \cos\beta - x \sin\beta$ (fig. 3) and the total vertical displacement of point c is

$$\frac{\alpha}{h} \Sigma \Delta u \, (y \cos\beta - x \sin\beta) \qquad (1)$$

But $\Delta u \cos \beta$ is Δx and $\Delta u \sin \beta$ is Δy and making these substitutions the vertical displacement of point c becomes

$$\frac{\alpha}{h} \Sigma (y \Delta x - x \Delta y) \tag{2}$$

The value of the line integral $\Sigma(y \Delta x - x \Delta y)$ is equal to twice the area under the curve (figure 3), and this area can be represented by the product of the width, w, and the average thickness, t, of the panel. Hence, the vertical displacement of c is $2 \alpha wt/h$.

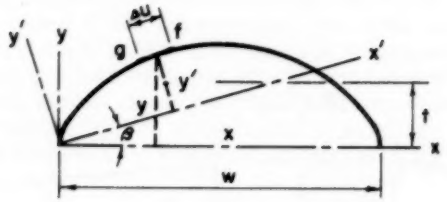


Figure 3

Taking the component of this vertical displacement of point c along the diagonal chord ac, we have that the change in length of the diagonal distance ac produced by the twisting of the surface is

$$\delta_o = 2 \frac{\alpha wt}{h} \times \frac{h}{m} = 2 \frac{\alpha wt}{m}$$

in which m is the length of the diagonal chord ac.

Lock-gate leaves may be subdivided into any number of panels either horizontally or vertically (figure 4). If D represents the total amount by which the miter end of the leaf is out of plumb, the angle α for any panel is (D/v) (h/H) and substituting this in the expression for δ_o we have

$$\delta_o = \pm 2 \frac{Dhwt}{Hvm} \tag{3}$$

Equation (3) is a general equation referring to either diagonal ac or diagonal bd for it is evident that for small angles of twist diagonal bd decreases in length by the same amount that ac increases in length. If the twist is in the opposite direction, diagonal ac will decrease in length while bd will increase.

On the right-hand side of equation (3) all factors except D are dimensions of the leaf and may be combined into a single constant, R_o, whence

$$\delta_o = R_o D \tag{4}$$

in which equation

$$R_o = \pm \frac{2 wht}{Hvm} \tag{5}$$

The values of R_o are not necessarily the same for all panels, but will vary with the dimensions of the panel. The sign of R_o is positive for positive diagonals, that is those which increase in length with a positive deflection, D,

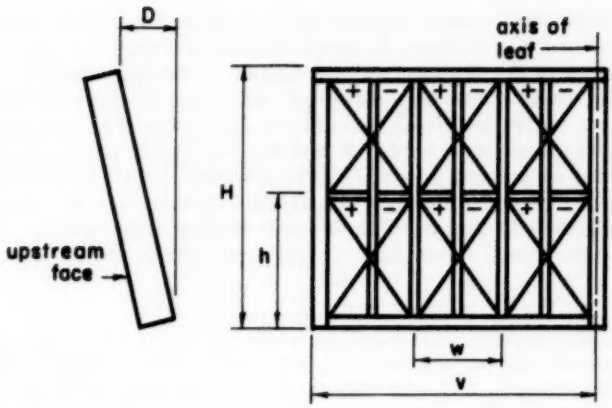


Figure 4

of the leaf. R_o is negative for negative diagonals which are those which decrease in length with a positive deflection of the leaf. D is considered positive when the top of the leaf is twisted upstream regardless of which of the leaves of the gate is being considered. A positive deflection is shown in figure 4 and the positive and negative diagonals are marked.

Consider a leaf with one diagonal member, figure 5. The leaf is initially vertical and there is no stress in the diagonal member. A force, F, applied as shown will twist the leaf and in doing so will do an amount of work equal to (F/2) (r/H) (z/v)D. Assuming that the leaf itself without a diagonal member has a negligible resistance to twisting (this will be true if the leaf does not have skin plates on both faces over any large part of its area) all of the work done by F can be equated to the work done by the stress, S, in the diagonal member. The work done by this stress is (S/2) δ_o which is (S/2)R_oD. Equating this to the work done by F and rearranging,

$$S R_o H v = F r z \qquad (6)$$

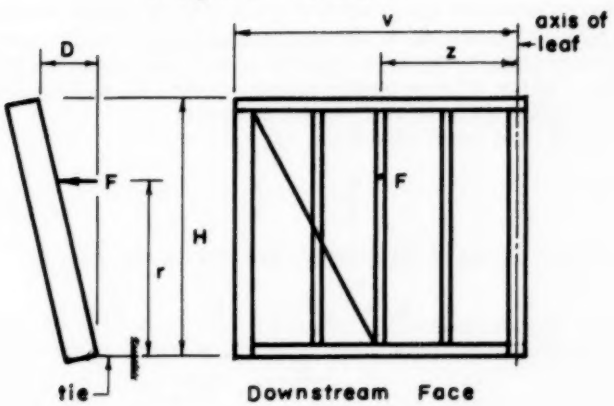


Figure 5

Suppose that the diagonal member of figure 5 had not been connected at the upper end and a deflection, D, had been imposed upon the leaf. The gap between the end of the diagonal and the corner of the panel would be $\delta_o = R_o D$, figure 6a. Now let a stress, S, sufficient to close the gap be applied while the deflection, D, is maintained, figure 6b. The diagonal member will elongate an amount $\delta = SL/AE$ and the corners of the panel will be pulled together an amount $\delta' = SL'/A'E$ in which L'/A' is a measure of the flexibility of the panel in the direction of the diagonal. L'/A' cannot be evaluated analytically inasmuch as so many factors enter into it. However, it has been determined experimentally for a number of different gates by

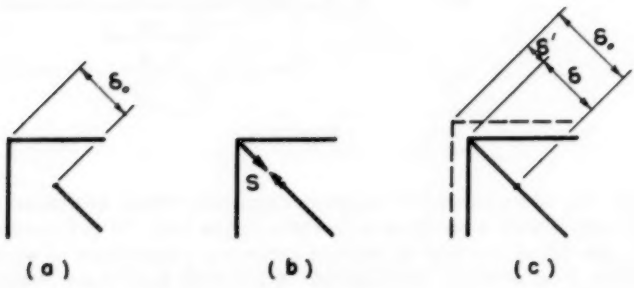


Figure 6

computing, for a given value of D, the strain δ and the stress S in the diagonal from strain gauge measurements. δ' is then the difference between the calculated value of δ_o and the measured value of δ and from this L'/A' can be found.

Even when a gate leaf has many panels the value of S as determined from the torsional loads is affected very little or not at all by the value of L'/A'. The computed deflection of the leaf is influenced by the value of L'/A' but even here the influence is not great because L'/A' is usually small compared with L/A and hence δ' is correspondingly small compared with δ.

If L' is taken arbitrarily to be equal to L, then experiments show that without serious error A' may be taken equal to one half of the average cross-sectional area of the girders which bound the panel.

Let $K = L/A$ and let $K' = L'/A'$.

Then
$$\frac{\delta}{\delta'} = \frac{K}{K'}$$

Substituting $(\delta_o - \delta)$ for δ', figure 7c, and solving for δ,

$$\delta = \frac{K}{K + K'} \delta_o \qquad (7)$$

$$= \frac{K}{K + K'} R_o D \qquad (7a)$$

The coefficient of D in equation (7a) is a constant for any particular diagonal member.

Let $$\frac{K}{K + K'} R_o = R \tag{8}$$

whence $$\delta = RD \tag{9}$$

The total stress, S, in any diagonal member is

$$S = \frac{\delta}{L} EA$$

$$= \frac{REA}{L} D$$

In the foregoing it was assumed that when D = 0 (leaf vertical) there is no stress in the diagonal. However, if the point of zero stress for a diagonal occurs at some other position, D_o, of the leaf then the elongation of the diagonal member is $R(D - D_o)$ and the total stress in the diagonal member is

$$S = \frac{REA}{L}(D - D_o) \tag{10}$$

Substituting this value into equation (6),

$$\frac{R_o H v REA}{L}(D - D_o) = Frz \tag{11}$$

For any given diagonal member the coefficient of $(D - D_o)$ is a constant. Furthermore, the constant is always positive for both positive and negative diagonals since R_o and R always have the same sign. Let Q represent this constant.

$$\frac{R_o H v REA}{L} = Q \tag{12}$$

Then

$$Q(D - D_o) = Frz \tag{13}$$

Q is an elastic constant of the diagonal member which measures the resistance which that member offers to the torsional deflection of the leaf. For more than one diagonal and for any number of loads,

$$\Sigma Q(D - D_o) = \Sigma Frz \tag{14}$$

and solving for D,

$$D = \frac{\Sigma Frz + \Sigma QD_o}{\Sigma Q} \tag{15}$$

For the leaf to hang vertically (D = 0) under its own weight the numerator on the right-hand side of equation (15) must equal zero for dead load.

$$(Frz)_{D.L.} + \Sigma QD_o = 0 \tag{16}$$

The value of F in this equation is the total dead-load weight of the leaf, r is the distance from the center of gravity of the leaf to the shear center of the leaf cross section, and z is the distance from the centerline of the pintle to the center of gravity of the leaf, all of which are shown in figure 7.

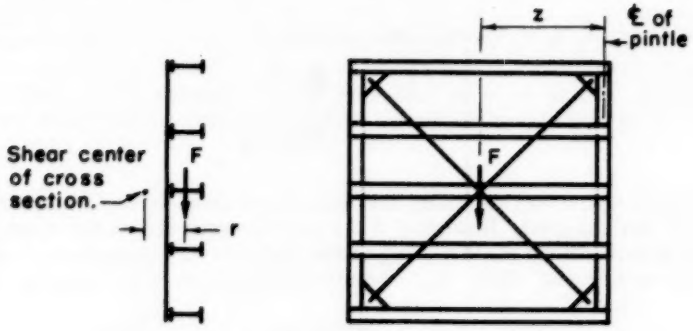


Figure 7

Separating L.L. and D.L. in equation (15),

$$D = \frac{(\Sigma\, Frz)_{L.L.} + (Frz)_{D.L.} + \Sigma\, QD_o}{\Sigma\, Q}$$

But $$(Frz)_{D.L.} + \Sigma\, QD_o = 0$$

Hence, when the leaf is being operated the torsional deflection will be

$$D = \frac{(\Sigma\, Frz)_{L.L.}}{\Sigma\, Q} \qquad (17)$$

If the diagonal members have sufficient initial prestress so that the stress in none of them is ever reduced to zero regardless of the amount of torsional deflection, then in equation (17) ΣQ includes all diagonal members whether positive or negative.. If the summation of the torsional live loads is positive, D will be positive; the stress in the positive diagonals will increase and the stress in the negative diagonals will decrease. The negative diagonals, in giving up some of their tensile stress, behave exactly as if they were capable of withstanding compression and they add just as much to the torsional stiffness of the leaf. For negative values of ΣFrz the function of the positive and negative diagonals is reversed. It has been assumed that diagonal members are so slender that they cannot sustain compression; if this were not so, the foregoing analysis would still be valid but prestressing would not be necessary.

Any horizontal axis parallel to the leaf and lying in the same vertical plane as the shear center may be used in computing the values of r, the torque radius. One such choice of axes is shown in figure 8. For any given condition of loading the value of ΣFrz is independent of the axis chosen.

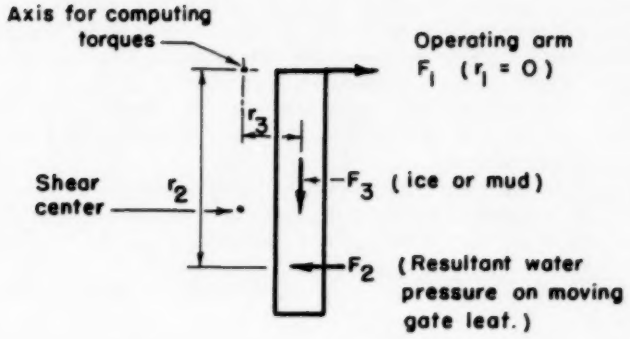


Figure 8

Design

The following steps should be taken in applying the theory to a design problem:

(1) Design the leaf completely except for the diagonal members. Make provision for the diagonal members as far from the skin plate as practicable. Do not increase the thickness of the leaf, however, beyond that which is required by other considerations.

(2) Compute the value of R_0 from equation (5) for each diagonal. For greatest efficiency all values should be approximately the same. Any diagonal with a very low value of R_0 might just as well be omitted since it will be very ineffective anyway. It is not necessary to have diagonal members in every panel.

(3) Compute the maximum positive and negative dead-load plus live-load values of Σ Frz. Using an average value of R_0 and the maximum positive value of Σ Frz determine the total of the stresses in all positive diagonals from equation (6).

$$\Sigma S = \frac{\Sigma Frz}{R_o Hv}$$

By dividing the total of the stresses, ΣS, by the number of positive diagonals the stress in each is obtained and the required size can be determined. All positive diagonal members should be made the same size regardless of their position on the leaf. Similarly determine the required sizes of the negative diagonal members using the maximum negative value of Σ Frz.

(4) Calculate the value of Q for each diagonal from equation (12).

(5) Using the maximum positive and maximum negative values of Σ Frz for live load only compute the maximum positive and maximum negative values respectively of the torsional deflection, D, of the leaf from equation (17). In each computation ΣQ contains all diagonals both positive and negative.

(6) Select a negative value of the prestress deflection, D_o, for the positive diagonals which is slightly greater numerically than the maximum negative deflection computed from equation (17). With this value of D_o the diagonals will never become slack during operation of the gates. Then select a positive value of D_o for the negative diagonals such that it is slightly greater than the expected positive deflection of the leaf. The values of D_o may have to be adjusted somewhat to satisfy equation (16) in order for the leaf to hang plumb under its own weight.

(7) Inasmuch as the stresses computed in step number 3 may not be exact, they should now be checked for each diagonal by using equation (10). If it is found necessary to revise the size of any member, all of the design steps will have to be repeated, but such repetition will not usually be necessary.

(8) Details of the diagonal members may now be worked out and the design is then complete.

Diagonal members which are adjustable by means of a turnbuckle or sleeve nut are the best type. The initial adjustment is easy and if the gate should become damaged in subsequent service it is a simple matter to readjust. However, adjustable diagonals are not necessary.

Field Work

The diagonals with the largest numerical amount of prestress deflection, D_o, should be adjusted first. Let us take an example in which the negative diagonals have the greatest amount of prestress. The following procedure should then be used.

Swing the leaf against the lock wall and tie the top to the wall. Then jack the bottom away from the wall until the leaf has a positive twist equal to the amount of the prestress deflection desired for the negative diagonals. At this point the turnbuckles in the negative diagonals should be tightened just enough to remove all slack but not so much that there is any great amount of stress in the members. During this operation the positive diagonals should be kept loose.

Now hold the bottom of the leaf and jack the top away from the wall until the leaf has a negative twist equal to the prestress deflection required for the positive diagonals. At this point remove all the slack from the positive diagonals. When the leaf is then released it will hang plumb and in operation it will be rigid.

If a diagonal member is not adjustable but is of fixed length it may be attached (by welding) when the leaf is in the proper position, D_o, for that diagonal. It should have no slack in it when it is attached or else D_o may be increased slightly to compensate for any slack which might exist.